REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
09/05/2017	Final	1 Jun 11 to 30 May 17

4. TITLE AND SUBTITLE
Mountain Terrain Atmospheric Modeling and Observations (MATERHORN) Program

5a. CONTRACT NUMBER

5b. GRANT NUMBER
N00014-11-1-0709

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
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5d. PROJECT NUMBER
16PR03096

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
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8. PERFORMING ORGANIZATION REPORT NUMBER
Final

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Office of Naval Research
875 North Randolph Street
Arlington, VA 22203-19951

10. SPONSOR/MONITOR'S ACRONYM(S)
ONR BD025

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT
The prediction of weather in complex terrain is a difficult challenge due to a host of physical and thermodynamic processes and numerical issues involved. While many theoretical and observational studies have been conducted on flow over gradually varying low slopes (hills), flow over high mountains with steep slopes of practical consequence under diurnal forcing still remains an understudied topic. The atmospheric boundary layer therein is forced by diurnal thermal forcing (valley and slope flows), large-scale synoptic influence or a combination thereof, and in all cases the boundary layer is replete with interesting sub-grid scale phenomena that are paramount for mesoscale modeling. Continued on final report

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Michael Zenk
					19b. TELEPHONE NUMBER *(Include area code)*
U	U	U	UU	40	574-631-9972

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MOUNTAIN TERRAIN ATMOSPHERIC MODELING AND OBSERVATIONS (MATERHORN) PROGRAM

Abstract

The prediction of weather in complex terrain continues to be a difficult challenge due to a host of physical and thermodynamic processes and numerical issues involved. While many theoretical and observational studies have been conducted on flow over gradually varying low slopes (hills), flow over high mountains with steep slopes of practical consequence under diurnal forcing still remains an understudied topic. The atmospheric boundary layer therein is forced by diurnal thermal forcing (valley and slope flows), large-scale synoptic influence or a combination thereof, and in all cases the boundary layer is replete with interesting sub-grid scale phenomena that are paramount for mesoscale modeling. Parameterizations of such processes, reducing model errors and their growth, model validations and new technologies for measurements are some of the overarching issues that need to be addressed in improving weather predictions in mountainous terrain. To this end, the MATERHORN program was conceived in response to the 2011 Multidisciplinary University Research Initiative (MURI) of the Department of Defense to address scientific issues akin to mountain weather. The participants include the University of Notre Dame, Naval Post Graduate School, University of California at Berkeley, University of Utah, University of Virginia, Naval Research Laboratory, US Army Dugway Proving Ground (DPG) and the Army Research Laboratory. The MATERHORN includes a comprehensive field experiments (MATERHORN-X) in the Granite Mountain Atmospheric Test Bed (GMAST) of DPG and a fog experiment in the Heber and Salt Lake valleys in Utah. This report presents the scientific outcomes and broader impacts of the MATERHORN project.

MOUNTAIN TERRAIN ATMOSPHERIC MODELING AND OBSERVATIONS (MATERHORN) PROGRAM

ONR FY 2011 MURI TOPIC #7: Improved Meteorological Modeling in Mountain Terrain

Project Website: www.nd.edu/~dynamics/materhorn

Agency: Office of Naval Research
(Topic Chiefs: Dr. Ronald J. Ferek and CDR Daniel Eleuterio, PhD)

Grant Number: # N00014-11-1-0709

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University of Utah (Eric Pardyjak, PI; co-PIs – Sebastian Hoch, James Steenburgh, David Whiteman, Zhaoxia Pu)
University of Virginia (Stephan F.J. de Wekker, PI)

Partners with Alternative Funding
Professors Ben Balsley and Dale Lawrence, University of Colorado, Boulder (Host: Notre Dame) – Sponsor: Army Research Office to deploy Datahawk UAVs in MATERHORN-1
Dr. David Emmitt, Simpson Weather Associates (Hosts: Notre Dame and University of Virginia) – Sponsor: Army Research Office to deploy TOWDL (Twin Otter Aircraft) in MATERHORN-1
Dr. Yansen Wang, Army Research Office (Host: Notre Dame) – Sponsor: Air Force Weather Agency (AFWA) to deploy Leosphere Scanning Lidar in MATERHORN-1

Unfunded Partners Actively Participating in the Project (Collaborators)
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Dr. Nick Ovenden and Prof. Julian Hunt, University College, London, U.K. (Host: Notre Dame)
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List of Accomplishments

- The first investigator (kick off) meeting was held on September 8, 2011, at University of Utah. A field trip was organized to visit the Granite Mountain Test Bed. More than 40 participants joined the meeting (http://www3.nd.edu/~dynamics/materhorn/kickoffmeeting.html).
- The second investigator meeting was held at University of Utah on 17th August 2012, with 35 participants (http://www3.nd.edu/~dynamics/materhorn/investigator_presentations.html).
- The MATERHORN-1 Experiment was successfully conducted during September 25 to October 25, 2012. It dealt with thermally driven flows in mountain terrain in the presence of weak synoptic wind. This included the participation of more than 30 field personnel in instrument deployment and data acquisition. A host of equipment was deployed, including airborne assets such as the Navy Twin Otter (TOWDL) and University of Colorado Data Hawk UAVs.
- WRF real-time forecasting support was conducted during the Fall 2012 MATERHORN field experiment.
- All the MATERHORN-1 data were pre-processed and Quality Controlled, and a new server system was set up at Notre Dame for the investigators to download data (materhorn.ce.nd.edu).
- The immersed boundary method in WRF as applied to GMAST terrain was investigated, and resolution and slope criteria to minimize numerical errors due to terrain following coordinate transformation were developed.
- A new drag law (logarithmic) as the bottom boundary condition for the immersed boundary method in WRF was developed and tested.
- Large-eddy simulation of intermittent turbulence generation under quiescent conditions in Owens Valley using 50 m grid spacing was conducted.

- Two autumns of operational runs by the NCAR 4DWX, performed with 9-member land-surface ensembles of three events, including two from the MATERHORN-X Fall period, were analyzed. They illustrate that the existing thermal conductivity parameterization in the WRF is inadequate at low soil moisture and that substantial forecast improvements can be obtained using an alternative parameterization for low soil moisture. It also shows that the lack of comprehensive and reliable soil-moisture observations on scales consistent with the local topography continue to remain an Achilles heel.
- Ensemble sensitivity runs were completed for Salt Lake City airport and Rocky Mountain wind storm. A localization theory was derived, and localization factors computed. Basic ensemble sensitivity methods were evaluated for a fog event in complex terrain. Strengths and weaknesses were evaluated and reported.
- A localization theory for ensemble sensitivities was derived, and localization factors computed. The deleterious effects of a widely used approximation were demonstrated, and shown to be acute for data voids and in the presence of model error.
- Initial WRF simulations on the interactions of mountain and valley flows were completed at Notre Dame, which helped placing instrumentations for the two MATERHORN experiments. University of Utah is working on high-resolution WRF analysis and data assimilation for MATERHORN Fall 2012 IOPs.
- Laboratory experiments on slope-valley flows have been completed; a criterion for flow separation on mountains was derived. New physics delineated in these experiments will be checked in the MATERHORN-2 Experiment.
- Data from a number of previous field studies were analyzed to deduce new information on mountain terrain flows. These included the Vertical Transport and Mixing Experiment (VTMX) in Salt Lake City, Ballast Experiment in France, Meteo-diffusion experiment in Italy, the Hermosa Park Experiment and TRANSFLEX experiment in Phoenix, Arizona, and the Terrain-Induced Rotor Experiment (T-REX) in Owens Valley, California. Most of this initial work has been published or is under consideration for publication.
- The engineering and development of a sensor system, simultaneously employing 3 frequencies (470 MHz, 915 MHz, and 2.4 GHz) and deploying the system with an automated data collection feature at Dugway, were completed. A potential approach for soil moisture estimation using a unique form of calibration based on topology knowledge was proposed (an invention - has not yet been disclosed). Mathematical models to evaluate this approach are being developed.
- An unmanned aerial vehicle carrying turbulence probes was developed for measurements of atmospheric flow from meso- to Kolmogorov scales. All signal processing devices as well as algorithms were designed and developed for data processing. The operations of the UAV is being moved to White Sands Missile range for convenience of operations.
- Developed new methods to improve retrieval of surface layer winds from airborne Doppler lidar (for NPS Twin Otter data).
- Developed new methods to determine stationarity in turbulence time series and evaluate Monin-Obukhov similarity theory in complex terrain. Analysis was conducted on PBL heights during MATERHORN-1 from 4DWX model output.

- Evaluated near-surface temperature and energy balance biases in the WRF, identified error sources, and illustrated a pathway to improved land-surface parameterization (see Massey et al. 2014).
- Determined the spatial and temporal variability of soil moisture over the Great Salt Lake desert and linked to heterogeneity in atmospheric evaporative process.
- During both MATERHORN Fall 2012 and Spring 2013 campaigns, real-time forecasts with WRF were executed at high resolution (~1 km horizontal grid intervals), initialized four times per day (at 00, 06, 18, and 24 UTC), which, as mentioned, supported the go/no-go decisions for IOPs. After the field programs, the forecast results were evaluated against high-resolution observations, which was particularly helpful in model performance evaluation and devising improvements (Pu et al. 2014).
- The impact of data assimilation and resolution on the predictability of atmospheric conditions over complex terrain is being evaluated using the WRF model, with an ensemble Kalman filter (EnKF) system developed by NCAR's Data Assimilation Research Testbed (DART; Anderson et al. 2009), with assimilation of radiosonde and surface mesonet observations of both campaigns. A month-long, 3-hourly continuous data assimilation and forecast cycle was conducted for evaluating the predictability of near-surface atmospheric conditions over DPG (Zhang & Pu 2014). Results illustrated that the quality of EnKF/WRF analysis is generally reasonable and the short-range (3h) forecast errors are comparable to those of NCEP's NAM forecasts for both 10m wind speed and temperature. With the data assimilation, the model reproduced reasonable forecasts of various synoptic and local flows, including mountain/valley circulations and a frontal passage. The flow features over different land types were also distinguished. Diurnally varying model biases were evident, indicative of a model inadequacy.
- Spatial variability of winds and PBL height was analyzed using airborne Doppler wind lidar measurements from MATERHORN-1.
- Turbulence Kinetic Energy and turbulent fluxes were analyzed from in-situ measurements of the Navy Twin Otter during MATERHORN-1.
- The relative contribution of complex topography and land-surface heterogeneity on the spatial variability in PBL height was investigated using large-eddy-simulations.
- The sensitivity of the 4DWX operational model to the assimilation of wind profiles from the airborne Doppler wind lidar was investigated.
- Near-surface wind, temperature and pressure fields from 4DWX were analyzed to identify the most favorable regions for the onset of boundary-layer separation.
- The MATERHORN-Spring Experiment during May 1-30, 2013, has been completed, which dealt with the synoptic flow influence on mountain terrain flows.
- An unmanned aerial system consisting of a hexa-copter and meteorological sensors was developed for collecting vertical profiles of temperature, humidity, and wind from the surface to 400 ft AGL.
- Idealized simulations completed to investigate soil moisture effects over steep terrain (Owens Valley) and over rolling hills.

- Immersed boundary method validated for flow over flat terrain with a logarithmic drag law and surface fluxes. Sloping surfaces are being tested.
- A new series of experiments on slope/valley flow collisions were initiated in September 2014. This follows the acquisition of a new Laser Doppler Velocimetry system for the measurement of two velocity components, attached with a Laser-Induced Fluorescence system for the measurements of buoyancy fluxes. The experiment is augmented with a state-of-the art Particle Image Velocimetry system. The laboratory and field measurements of fluxes due to collisions can be directly compared.
- An efficacy of the triple-Lidar concept for three-dimensional space-time distribution of velocity vector was demonstrated. A paper in this regard was published. This is an important development of MATERHORN-T.
- The combo hot film-sonic anemometer system that was developed for MATERHORN-T and deployed in both MATERHORN experiments (Spring and Fall) adduced new physics of stratified turbulence, in that there are small scale production of turbulence at high wave number regime that cannot be resolved by sonic anemometers. This was attributed to the 'critical layer absorption' phenomenon active in stratified shear flows, where internal waves are degenerated in the critical layer.
- A new formulation was presented for the 'dividing streamline concept' where now the dividing streamline height can be calculated reckoning the effects of velocity shear. A new parameterization was proposed to account for shear in approach flow to a mountain, taking into account the stratification effects. All these were driven by observations made in MATERHORN experiments.
- A successful (Fourth) investigator meeting was held at University of Utah, with twenty-seven participants. Information and presentations are being posted.

  http://www3.nd.edu/~dynamics/materhorn/news.php
- MATERHORN-Fog experiment was conducted during January 7, 2015 to March, 31, 2015, with ten IOPs. The experiment was participated by three MURI institutions: University of Utah, University of Notre Dame and University of Virginia. A significant development is the participation of Environment Canada by providing a comprehensive suite of instrumentation and skilled researchers (Drs. Ismael Gultepe and Michael Harwood). NCAR has also provided some instrumentation.
- The MATERHORN-Fog was designed to understand the life cycle of fog events in either high-altitude alpine basins (in Heber Valley) or larger-scale urbanized valleys (Salt Lake City). Virtually no detailed studies exist on fog formation over complex terrain. The instrumentation deployed included tethered- and radio-soundings, several flux towers, sodars and Lidars and different types of particle counters as well as visibility and precipitation measurement instrumentation. Analyses are mainly based on observations of ice particle and aerosol spectral characteristics, visibility (Vis) due to fog and precipitation, fog ceiling, wind and turbulence, radiative fluxes and their divergences. Data of selected fog events were analyzed for extinction calculations. Possible ice nucleation (IN) processes were also studied. Assuming that ice fog occurs usually when relative humidity with respect to water (RH_w) is less than 100%, a relationship between RH_i (RH with respect to ice) and Vis was obtained. Based on ice microphysical spectral observations, the influence of both ice water content (IWC) and ice

crystal number concentration (N_i) on the extinction were investigated, and a new parameterization was proposed.

- The distribution and frequency of fog events during the cold season in northern Utah was studied using surface Mesowest data from 2004 to 2014. Fog was identified using the reported weather conditions, relative humidity, and visibility. Statistics are performed on daily, monthly, and seasonal timescales. Results show that there is significant variability among the valleys in northern Utah in terms of both quantity and timing of fog events. In addition, the influence of local, mesoscale conditions on the fog distribution was evident in many stations (Hodges & Pu 2015). The controlling factors that contribute to the variability of fog events over mountainous northern Utah were also investigated. The outcomes from this study were helpful for planning the MATERHORN-Fog field experiment.
- During the MATERHORN-Fog field experiment (January to March 2015), real-time forecasts with WRF were executed by Professor Zhaoxia Pu at high resolution (~1 km horizontal grid intervals), initialized two times per day (at 00 and 12 UTC), which supported the go/no-go decisions for IOPs. After the field programs, the forecast results were evaluated by the University of Utah group. The model outputs were compared against sounding observations at both Salt Lake City and Heber City, surface Mesonet data in both Salt Lake and Heber valleys. Results were particularly helpful in model performance evaluation (Chachere et al. 2015).
- Some of the MATERHORN PIs were invited to participate in the planning of the Perdigão experiment in Portugal, a complex-terrain field experiment on microscale processes, conducted under a European ERANET+ Project called *New European Wind Atlas* (NEWA). A SPO/EDO proposal was submitted to NSF for the participation, and this was a natural extension of the MATERHORN science plans from mesoscale to microscales. The SPO was funded by NSF on July 23, 2015, testifying to the success of MATERHORN and the credibility of the MATERHORN organization and science enterprise. Three MATERHORN PIs participated in the SPO/EDO Process.
- The deployments over the extensive MATERHORN observations period provided an opportunity to observe turbulence over a vast range of background flow and stratification conditions. Of particular interest was a stable stratified period over which the flow slowly transitioned from an almost laminar flow regime to a fully developed turbulent flow regime. During this phase, the combo (combined sonic and hot film) probes revealed an intriguing phenomenon - the occurrence of strong bursting events at finer scales that generate turbulence. In the absence of bursting, say in convective boundary layer periods or low stabilities, the spectra takes the form of classical Kolmogorov turbulence, while the presence of bursting leads to a spectral shape resembling that of the bottleneck effect, where a bump in the spectrum appears between the inertial and dissipation subranges. A possible explanation was provided for these observations, and the problems associated with measuring dissipation using sonic measurements were delineated (Kit et al. 2017). Following this discovery, the Israeli collaborator received a grant from the Israeli Science Foundation to study this phenomenon further.
- Completed a set of numerical experiments examining the impact of regional-scale soil moisture analysis biases on WRF temperature and stability forecasts over the MATERHORN study area. Accounting for these biases significantly improves forecasts over the region, and suggests that observations from the recently launched NASA Soil Moisture Active Passive

(SMAP) mission could be used to significantly improve forecasts in other arid mountainous regions.

- A novel method was developed to assimilate near-surface winds and temperatures that have systematic departures from a model. Because of finite grid spacing (truncation), which affects model-simulated boundary layer structure, terrain details, and other sub-grid scale land-surface variability, a model prediction and observation can be systematically different even if both are perfect within their own atmosphere, respectively, the model and real atmosphere. Inspired by satellite observing bias correction, the difference between predicted observations and a real observation as an observation bias was treated, and a term in the data assimilation forward operator that can be optimized in the data assimilation system itself was introduced. Results from experiments with a simple model show that the systematic difference between model and observation can be corrected in a variety of observing scenarios. It works because the model can extract information from the observation, even if the observation does not lie on the model attractor.
- The work on systematic observation error was extended to include systematic model error. There are improved analyses and predictions, and simultaneous estimates to the systematic observation and model error itself. Results demonstrate a general approach to simultaneous observation and model errors, where both are large in complex terrain. The paper has been published in *Monthly Weather Review* (http://journals.ametsoc.org/doi/abs/10.1175/MWR-D-16-0273.1).
- Several implementations of the logarithmic drag law for surface momentum and heat fluxes have been tested inside WRF to determine the most accurate approach, given WRF's pressure-based coordinate system. The methods have been extensively tested for flow over flat terrain with laminar and turbulent flow conditions and different turbulent closure models. The implementations are being extended to more general conditions.
- Idealized simulations of flow over Askervein Hill are being used as another testbed for the immersed boundary method implementation comparing no–slip to a shear-stress reconstruction method for log-law boundary conditions.
- Completed case study analysis of one evening transition and nocturnal boundary layer evolution on the East Slope of Granite Mountain. The data indicated the existence of three distinct phases: an evening transition governed by the propagation of a shadow front followed by a 3–4-h period of almost steady-state boundary layer conditions, with a shallow slope-parallel surface inversion and a pronounced downslope flow. The shallow slope boundary layer was very sensitive to ambient flows. During the final phase, which started just before midnight, the adjacent valley cold pool repeatedly sloshed up the mountain sidewall, disturbing local downslope flows and causing rapid temperature drops.
- Completed analysis of counter-gradient heat fluxes, which were regularly observed over the Dugway Playa and Sagebrush regions during evening transitions. The transition process is both site and height dependent. The temperature gradient sign reversal was found to be a top-down process, while the flux reversal occurs nearly simultaneously at all heights. Differences between the two sites were primarily due to the different subsurface thermal characteristics at the two sites. The combined high volumetric heat capacity and high thermal conductivity at the Playa site lead to small vertical temperature gradients that affect the relative magnitude of terms in the heat-flux tendency equation. A critical ratio of the gradient production to buoyant production of sensible heat flux is suggested so as to predict the counter-gradient behavior.

- Completed analysis soil moisture and evaporation dynamics for the Dugway Playa regions during the synoptically active spring period. The results show that following rain events decreasing of surface albedo, decreasing Bowen ratio and increasing net radiation sustain a powerful positive feedback mechanism promoting large evaporation rates. Additionally, it was found that nocturnal evaporation was quite significant during nights following rain events. The highest spatial variability in surface soil moisture is found under dry conditions, while strong spatial heterogeneities in evaporation rates are observed following rain events.
- High-resolution simulations of standard WRF over Granite Mountain are being setup using high-resolution land-surface data with comparison to observations. These will be extended to higher resolution with the immersed boundary method when implementation is complete.
- Grid nesting from WRF to WRF-IBM has been implemented and is being tested over flat terrain. This required updates to WRF's nesting code including many details in the parallelization routines.
- Developed a theoretical approach for soil moisture retrieval that is derived from full-polarization measurements. The goal of the approach is to use Fresnel reflection coefficients and propagation statistics along with soil composition characterizations to facilitate soil moisture retrieval. The approach is designed to minimize uncertainties due to surface roughness. Simulation results indicate the efficacy of the approach, although the methods depend upon explicit knowledge of antenna patterns. Therefore, preliminary conclusions (until extensive measurements are collected) are that some form of calibration will be required for the inversion processing.
- Built-up a full-polarization RF sounding system for comprehensive RF system measurements using a large collection of laboratory equipment to provide range-gated full-polarization measurements with beam-forming to permit evaluation, validation, and comparison of techniques with different inversion methodologies proposed in literature. The purpose of such a sounding system is to facilitate comparison of different techniques reported in literature (power-based) and polarization techniques that exploit phase coherent signals. The system implementation was found to be impractical in preliminary experiments due to the lack of full integration of the large number of components. A resolution to this integration problem is provided by a $1M system acquired by Notre Dame on a DURIP grant. The system is being delivered in stages and although the final stage is due to be delivered in 4Q 2018, the system in its current state is beginning to be utilized. The system incorporate up to 4 dual-polarized transmit antennas (8 transmit ports) and 4 dual-polarized receive antennas (8 receive ports), with phase coherence preserved and with an anticipated tuning capability between 10 MHz and 20 GHz.
- Lower-cost alternatives including a (~$15,000) full-polarization sensor system with RF calibration offers potential to implement the polarization techniques being considered in our research. In contrast to the original system deployed at Dugway, which involved a single transmission, this system is a full-polarization system. In a typical configuration, the system does not provide range gating. However, on a separate project, an alternative configuration has been achieved with radar ranging capabilities. This full dual-polarization radar system is capable of 1m resolutions that have been used in preliminary field tests. To adapt the system to field scale measurements, long integration times will be required, and so that is a hurdle that will be crossed in the future.

- Testing with satellite signals was also considered, where we attempted to utilize inexpensive passive receivers to collect Dish satellite energy reflected from the ground. The commercial devices used to implement the desired approach was inadequate in multiple ways. Customization of satellite feeds to obtain synchronous received signals resulted in feeds that were operable for only approximately 2 hours. A separate issue was the need for long integration times to collect sufficient energy for suitable reflection characterizations. The data collection approach requires the use of FPGA-based processing, which was beyond the scope of our efforts. Recent equipment from a DURIP will enable such collections, and we are beginning to bring this system up to operational capability. An RF front ends needed for the passive satellite collection will be in place in 4Q of 2017, at which point the methods can be re-evaluated.
- A sophisticated laboratory experiment with a state of the art Particle-Image Velocimetry system and a Laser Induced Fluorescence system was set up to investigate mixing in colliding gravity currents. Such collisions were observed in MATERHORN fall (2012) and spring (2013) experiments, but the limitations of the instrumentation did not allow quantification of mixing efficiencies, posing problems in implementing conditional parameterizations in mesoscale models to account for collision-induced mixing. The new laboratory experiments allowed determination of eddy diffusivities as a function of governing parameterizations. New techniques needed to be developed to analyze such complex experiments with space-time inhomogeneities. Two papers, one on the technique has already been resubmitted after revisions, and the other presenting the results is being submitted.
- The analysis of small scale turbulence measured using combo probe systems during the first two MATERHORN experiments continued, after arriving at an important result that in the presence of bursting at large frequencies (in the high-frequency end of the inertial subrange) there is a substantial energy injection. This led to the argument that the rate of dissipation of turbulence in the atmospheric boundary layer in stratified periods may not be estimated using canonical formulae based on the energy cascade assumption. In addition, rigorous analyses conducted using the data has led to some new concepts of turbulence involving velocity gradient skewness, especially the modification of it in the presence of bursting. Before this work, there were no high quality velocity gradient data obtained with the resolution of dissipation scales.
- Substantial progress was made in the understanding of ice fog formation in complex terrain, based on the data of the MATERHORN-Fog experiment. Five journal papers have been published already (Guletepe et al. 2016; Hang et al. 2016; Pu et al. 2016; Hodges & Pu 2016; Chachere & Pu 2016), which include as assessment of predictability of fog in the experiment, the role of complex terrain processes in modulating flux during the experiments, development of microphysical parameterizations and understanding nucleation processes. Climatological studies were conducted for the Heber Valley and Salt Lake Valley, which are the two experimental areas.
- A special issue of MATERHORN studies have been edited and appeared in the journal Boundary Layer Meteorology. It is entitled: Mountainous Terrain: Results from MATERHORN-X (June 2016, Volume 159, Issue 3; Editor – Silvana Di Sabatino), and contained seven papers. This special edition complements the collection of papers in AMS journals (Organizer - Zhaoxia Pu). Another special issue focusing on fundamental processes is in preparation for the Journal of Environmental Fluid Mechanics (Editor – Eric Pardyjak and

Laura Leo). The special Fog Issue edited by Ismael Gultepe has a selection of MATERHORN papers.

- The participation of MATERHORN project directly led to other opportunities. In 2016, the National Science Foundation funded the Perdigao project, which deals with fine scale measurements related to microscale modeling of complex-terrain flows. This is a direct extension of the meso-scale emphasis of the MATERHORN project. Perdigao is the US counterpart of a large European Project known as NEWA (New European Wind Atlas), and the organizers reached out to the MATERHORN PI to facilitate the US participation. Army Research Laboratory (ARL) will also be a part of the Perdigao project, and at ARL it will be led by a former MATERHORN student/post-doc who is now at ARL. Some of the equipment procured through the MATERHORN project will be deployed in Perdigao. Additionally, some of the MATERHORN participants are engaged in the WFIP-2 (Wind Forecasting Improvement Project) funded by the Department of Energy, which has a special emphasis on complex terrain winds. Some of the MATERHORN participants have been invited to be in the Meteorological Review Committee for the 2022 Beijing Olympics. This committee is hosted by the Urban Meteorological Institute, Beijing.
- PI Fernando received a DURIP award to acquire a Triple-Lidar system, which is new technology based on the technology development efforts (MATERHORN-T). The instrument is currently developed by Halo Photonics Inc., UK and is scheduled to be delivered by October 2016. Another PI (de Wekker) also received a DURIP to acquire a Doppler Lidar system. In all, the MATEHORN Project has helped improve the research infrastructure of participating institutions.
- A substantial study on upslope flows has been completed by the Notre Dame group, which include theoretical, laboratory experimental and numerical work. This work is in part being funded by the US-Israeli Binational Science Foundation, and the Israeli PI of the project is a former post-doctoral fellow funded by MATERHORN, who is now a professor at Technion, Israel.
- The ARL participation in MATERHORN led to a resurgence of complex terrain Atmospheric Boundary Layer research at the ARL Atmospheric Sciences Center due to the breadth of ARL/MATERHORN participant scientific collaborations, publications, and conference presentations. MATERHORN scientific findings were fundamentally useful as guidance for future complex terrain basic research program formulation efforts at NRL. Furthermore, ARL has benefited vastly from MATERHORN – T technology and is continuing to pursue research in synchronized Doppler LiDARs and instrumented UAS for implementation in the ARL's upcoming Meteorological Sensor Array at White Sands Missile Range (POC: Chris Hocut, ARL White Sands Missile Range).
- NCAR 4DWX model output has been analyzed by the University of Virginia group, which has been compared with PBL depths simulated for different domains with different resolutions. Significant overestimations of PBL depths for the coarser domains have been noted. Case studies have been conducted to investigate the underlying processes for the overestimation and to develop a parameterization for PBL depths in coarse scale models.
- Six in-house developed low cost weather stations were deployed by the University of Virginia Group in MATERHON-FOG. They revealed the existence of gravity waves during ice-fog conditions based on the analysis of 1 Hz measurements of wind, temperature, humidity, and pressure. Further development of these sensors afoot.

- The University of Virginia group continues to develop and test algorithms to determine winds from multi-rotor copter-based measurements.
- A 17-year surface wind climatology based on available long-term observations at Dugway Proving Ground was compiled and analyzed to reveal the multi-scale forcing mechanisms and their diurnal and seasonal variations in the complex terrain of Northwest Utah. Wind regimes were identified that are related to the position of the primary synoptic baroclinic zone in the Western United States, interactions of the large scale flow with the Sierra Nevada, and the summertime thermal low pressure in the Intermountain West.
- A study investigated the causes of nocturnal large temperature fluctuation observed on the east side of Granite Mountain, highlighting the effects of cold air pool displacements along the alluvial fans in the complex terrain at Dugway Proving Ground. Under stably stratified westerly or southwesterly flow conditions, an orographic wake and an associated vertical axis vortex develops on the East Slope of Granite Peak, controlling the position of the large temperature gradient associated with the basin cold pool. These phenomena can be resolved by high-resolution WRF simulations and is a well-suited test case for future model validations.
- Clear-air radiative heating and cooling in the atmospheric surface layer was directly measured during MATERHORN-FOG. The observations indicate that radiative flux convergence during the day contributes substantially to the vertical transport of heat. Further analysis for both clear and fog conditions are underway. Nested simulations using standard WRF over Granite Mountain have been completed down to 100 m resolution (with proper choice of grid aspect ratio allowing such high horizontal resolution over the steep terrain). Comparisons with field data show great sensitivity to soil moisture when trying to capture large temperature fluctuations observed in the lee of the mountain wake. Additional IOP dates are being investigated.
- Semi-idealized simulations of thermally driven downslope flows over Granite Mountain have been performed by the Berkeley group at 50 m horizontal resolution using the immersed boundary method (IBM) in WRF. At this resolution the terrain slope reaches 55 degrees, which is too steep for WRF's native terrain-following coordinates to handle. The IBM has been coupled with the topographic shading routine in WRF. Comparison with field data shows good qualitative agreement and that the movement of the shadow front is correlated with the initiation of downslope flows along the slope.
- Rigorous testing of multiple implementations of the logarithmic drag law for surface momentum is being performed in WRF-IBM by the Berkeley group. The most accurate results are obtained when a shear stress reconstruction condition and a velocity boundary condition are set. This approach shows excellent agreement with expected profiles over flat terrain and over an idealized shallow valley. Comparison of other methods used in the literature shows that those methods are not able to capture the near-surface velocity profile accurately. Debugging and testing continues for different valley geometries.
- Work continues to enable grid nesting from standard WRF to and IBM domain. Because the alignment of the coordinates is different in each setup, the interpolation procedure used to transfer information between grids creates imbalances in the atmospheric variables, specifically in the standard 'rebalancing' step performed at initialization in WRF. Detailed investigation of the 'side effects' of this interpolation has introduced new potential solution paths which are being pursued.

- MATERHORN-Fog field data were used by the Utah group to better understand the evolution of fog in complex terrain. In particular, it was possible to gain insight into relationships between typical shallow radiation fog, turbulence, and gravity waves associated with the surrounding topography.
- The unprecedented dataset from the MATERHORN Spring and Fall campaigns, in particular those from the East Slope of Granite Mountain were used by the Utah Group to better understand the evolution and sensitivity of katabatic flow dynamics to external influences during the evening transition.
- The understanding gained by analyzing the turbulent kinetic energy (TKE) equation in light of MATERHORN data by the Utah Group clearly pointed to the importance of considering salient terms in the TKE equation when interpreting, modeling and designing future complex terrain experiments. In particular, the identification of the fact that vertical buoyancy fluxes in katabatic flows can be positive and a source of turbulent kinetic energy despite that overall flow is statically stable was a noteworthy finding.
- Completed an evaluation of WRF simulations during the Fall 2012 and Spring 2013 MATERHORN field campaigns relative to surface energy balance observations collected over contrasting desert shrub and playa land surfaces, identifying an under-prediction of sensible heat fluxes and over-prediction of ground heat fluxes over the former and an over-prediction of latent heat fluxes over the latter. Incorporation of in-situ soil moisture observations and a modified soil thermal conductivity parameterization improves the shortcomings over the desert shrub, but accurate simulation of the surface energy balance over playa remains challenging. Collectively, improvements in the simulated surface energy balance results in a stronger daytime off-playa breeze, but no substantial improvement in 10-m wind speed and direction mean absolute errors. Overall, this work highlights some of the deficiencies of land-surface modeling over arid land surfaces.
- An in-depth study on stratified flow over topography was completed at Notre Dame using high-resolution ARW-WRM simulations. New algorithms were developed for tracking streamlines using Matlab as a platform, thus enabling investigations on concepts such as dividing streamlines as well as model validations using hard-to use Lidar data. These algorithms are available for the use of future users, and a paper in this regard is in preparation.
- The Office of Naval Research has granted funding to the Earth Observing Laboratory of NCAR/UCAR to archive all the MATERHORN field data for the future use of the community. This will be available through a special web portal, and the data transfer is continuing: https://www.eol.ucar.edu/field_projects/materhorn-x.
- Given the mammoth data set, their collection from the investigators was challenging and time intensive, and considerable effort was needed from the part of ND group to develop this database.
- The special issue in the Journal of Environmental Fluid Mechanics is accepting papers, which will be the last special issue of MATERHORN. So far, seven papers are in the review process and four more contributions are expected.
- The paper describing the project "THE MATERHORN: Unraveling the Intricacies of Mountain Weather" published in the Bulletin of the American Meteorological Society Is listed as one of the most highly cited paper by ISI Web of science [quote: As of March/April 2017, this highly cited paper received enough citations to place it in the top 1% of the academic field of Geosciences based on a highly cited threshold for the field and publication year].

- The triple Lidar system funded under a DURIP grant was delivered to University of Notre Dame by the manufacturer, Halo Photonics Ltd. This is a result of technology development under MATERHOTN. This system is first of its kind in the USA. In the delivered system, however, the method of communication between Lidars was through hard wiring, which is not suitable for field implementation. Therefore, wireless communication system was developed in house, which included communication between Lidars through a set of antennas. The system was successfully deployed in the Perdigao field experiment in Portugal (May 1 – June 15, 2017), which was an upshot of the MAERHORN project. National Science Foundation funds the Perdigao project, and it deals with improving microscale predictions in complex terrain, thus complementing mesoscale focus of MATERHORN.
- Notre Dame Group continued data processing and analysis focusing on upslope flow, mixing in stable boundary layers as well fundamental aspects of turbulence. Manuscripts based on these studies have already being submitted or awaiting to be submitted. A manuscript based on laboratory experiments on collision of gravity currents have been prepared and awaiting comments from the authors. This comprehensive study delved into the nonstationary and inhomogeneous mixing processes, and involved adaptation of many state of the art data processing techniques.
- Turbulence structure in a deep, strong katabatic flow on an extensive plain near the Meteor Crater, Arizona, has been compared to the turbulence structure observed by Grachev et al. (2015) in a shallow katabatic flow at Granite Mountain. Turbulence in the deep flow does not extend up to the jet maximum height, suggesting that the jet maximum height may not be an appropriate non-dimensional height scale for katabatic flows of different depths. Richardson number computations provide an explanation for this phenomenon, as stability and shear act to suppress turbulence as the height of the jet maximum is approached.
- Diagnosed surface energy balance (SEB) components over desert-shrub and playa land surfaces, which were subsequently used to validate the WRF SEB. This showed the importance of accurate land-surface analyses for simulating the SEB over a dryland region, but also highlights some significant deficiencies in existing LSMs, especially for simulating the SEB over playa.
- UC Berkeley continued work on nested WRF simulations at 100 m resolution to analyze vertical axis eddies in the lee of Granite Mountain and associated large temperature fluctuations. Detailed comparisons to field lidar data indicate qualitative agreement with the model output showing slope flow transitions on the east slope of Granite Mountain.
- Testing of the WRF-IBM velocity reconstruction IBM method was completed by UCB for flow over Askervein Hill and Bolund Hill, with careful validation between WRF and WRF-IBM results. This velocity reconstruction approach has known errors but is simple to implement; errors are small enough to yield quite satisfactory results for these field test cases. The WRF-IBM results agree as well as or better than previous terrain-following coordinate simulations for the Askervein case. The Bolund case is too steep for terrain-following coordinates, but comparison to field data is quite good. Work continues on testing the more accurate hybrid velocity and shear stress reconstruction immersed boundary method.
- Work continues by the UCB group to enable grid nesting from standard WRF to an IBM domain. A new approach was taken to circumvent errors in the total column mass when interpolating from one vertical grid to another, by creating a new IBM implementation which does not use ghost cells so the total domain height is unchanged. Testing of idealized nested

domains has been successful, and work now continues to implement scalar flux conditions at the IB surface.

Program Products - Overall Statistics

Category	Total for 2011-2017
Organization of Meetings/Special Sessions	11
Journal Publications: Published or Accepted	68
Journal Papers Submitted or in Revision	13
Invited Presentations	31
Conference Papers	13
Conference Presentations	179
Awards	11
Recognitions	6
Number of Post Docs	18
Number of PhD Graduate Students	21
Number of MS Graduate Students	9
Number of Undergraduate Students	30

Organization of Meetings/Special Sessions (Total: 11)

A special AGU Session on Complex Terrain flows was organized by Stephan De Wekker (University of Virginia) and Fotini Chow (UC Berkeley), 2011 Fall Meeting.

Organized a special session on "Atmospheric Observations in Mountainous Terrain" at the 92nd American Meteorological Society Annual Meeting, January 22-26, 2012).

Organization of special session on "Atmospheric boundary layers in complex terrain and over ice, snow and vegetated surfaces" at the Davos Atmosphere and Cryosphere Assembly (DACA), 8-12 July 2013 by Stephan DeWekker.

Organized a special session on "MATERHORN Project" 94th AMS Annual Meeting in 2014, Atlanta, 2-6 February, by HJS Fernando, Josh Hacker, Eric Pardyjak, Stephen De Wekker and Tina Chow.

Organized a special session on "Research on Improving Weather Prediction for Mountain Terrain" at the AGU Fall Meeting, 9-13 December 2013, by Josh Hacker, Eric Pardyjak, Stephen De Wekker and Tina Chow.

Organized a special session on "Observations, Predictions, and Predictability of the Atmosphere Over Complex Terrain" at the AGU Fall Meeting, 15-19 December 2014 by Josh Hacker, H.J.S. Fernando and Eric Pardyjak.

Organized a Special session on: Observations and Predictability of the Atmosphere over Complex Terrain (Session ID: 8181), AGU Fall Meeting, 2015 by Eric Pardyjak, Daniel Nadeau, Josh Hacker and H.J.S. Fernando.

Organized a special session on Complex Terrain Flows, 19th Conference on Applications of Air Pollution Meteorology, American Meteorological Society, 96th Annual Meeting, 2016 (Laura Leo and H.J.S. Fernando).

Organized a special session: Results from the Mountain Terrain Atmospheric Modeling and Observations (MATERHORN) Project, at the 32nd Conf. on Agricultural and Forest Meteorology/22nd Symp. Boundary Layers and Turbulence/ Third Conf. on Atmospheric Biogeosciences , 20 – 24 June, 2016 (Eric Pardyjak)

Organized a special session on "Complex Terrain Effects" at the UC Davis Meteorology and Climate – Modeling for Air Quality Conference, 16-18 September 2015 (Tina Chow).

Organized a special session on "Complex Terrain Effects" at the UC Davis Meteorology and Climate – Modeling for Air Quality Conference, 13-15 September 2017 (Tina Chow).

Journal Publications: Published or In Press (Total: 68)

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Hang, C., Nadeau, D.F., Gultepe, I., Hoch, S.W., Roman-Cascon, C Pryor, K., Fernando, H.J.S., Creegan, E., Leo, L., Silver, Z. and Pardyjak, E., "A Case study of the mechanisms modulating the evolution of valley fog," *Pure and Applied Geophysics*, 173 (9), 3011-3030. DOI 10.1007/s00024-016-1370-4.

Hodges, D. & Pu, Z.. 2016: The Climatology, Frequency, and Distribution of Cold Season Fog Events in Northern Utah. *Pure Applied Geophysics*, 173, 3197. doi:10.1007/s00024-015-1187-6

Holmes, H. A., J. K. Sriramasamudram, E. R. Pardyjak, and C. D. Whiteman, 2015: Turbulent fluxes and pollutant mixing during wintertime air pollution episodes in complex terrain. *Environ. Science Technology*, 49(22),v13206-13214. doi: 10.1021/acs.est.5b02616.

Jensen, D.D., D.F. Nadeau, S.W. Hoch and E.R. Pardyjak, 2016: Observations of near-surface heat flux and temperature profiles through the early evening transition over contrasting surfaces, *Boundary-Layer Meteorology, 159*(3), 567-587. DOI: 10.1007/s10546-015-0067-z.

Leo, L.S., Thompson, M.Y., Di Sabatino, S., and Fernando, H.J.S., 2016: Stratified flow past a hill: Dividing Streamline Concept Revisited, *Boundary-Layer Meteorology*, 159 (3), 611-634.

Massey, J. D., W. J. Steenburgh, J. C. Knievel, and W. Y. Y. Cheng, 2016: Regional soil-moisture biases and their influence on WRF model temeprature forecasts over the Intermountain West. *Weather Forecasting*, 31, 197–216.

Nilsson, E., F. Lohou, M. Lothon, E. Pardyjak, L. Mahrt and C. Darbieu, Turbulence Kinetic Energy budget during the afternoon transition – Part 1: Observed surface TKE budget and boundary layer description for 10 intensive observation period days, *Atmospheric Chemistry and Physics*, 16, 8849–8872, 2016.

Nilsson, E., M. Lothon, F. Lohou, E. Pardyjak, O. Hartogensis, and C. Darbieu, Turbulence Kinetic Energy budget during the afternoon transition – Part 2: A simple TKE model. *Atmos. Chem. Phys.*, 16, 8873–8898, 2016.

Oldroyd, H.J., E.R. Pardyjak, C.W. Higgins, and M.B. Parlange, 2016: Buoyant turbulent kinetic energy production in steep-slope katabatic flow, *Boundary-Layer Meteorology*, DOI:10.1007/s10546-016-0184-3.

Pal, S., S.F.J. De Wekker, and G.D. Emmitt, 2016: Investigation of the spatial variability of the convective boundary layer heights over an isolated mountain: Cases from the MATERHORN-2012 Experiment. *Journal of Applied Meteorology and Climatology,* 55, 1927- 1952. DOI: 10.1175/JAMC-D-15-0277.1.

Palomaki, R.T., N.T. Rose, M. van den Bossche, T.J. Sherman, and S.F.J. De Wekker, 2017: Wind estimation in the lower atmosphere using multirotor aircraft. *Journal of Atmospheric and Oceanic Technol*ogy, 34, 1183–1191, https://doi.org/10.1175/JTECH-D-16-0177.1.

Pu, Z, C. N. Chachere, S. W. Hoch, E. Pardyjak and I. Gultepe, 2016: Numerical Prediction of Cold Season Fog Events over Complex Terrain: the Performance of the WRF Model During MATERHORN-Fog and Early Evaluation, *Pure and Applied Geophysics*, 1-22, doi:10.1007/s00024-016-1375-z.

Pu, Z., Chachere, C.N., Hoch, S.W., E. Pardyjak, 2016: Numerical Prediction of Cold Season Fog Events over Complex Terrain: the Performance of the WRF Model During MATERHORN-Fog and Early Evaluation, *Pure and Applied Geophysics,* 173, 3165. doi:10.1007/s00024-016-1375-z.

Van den Bossche, M., and S.F.J. De Wekker, 2016: Spatiotemporal variability of surface meteorological variables during fog and no-fog events in the Heber Valley, UT; selected case studies from MATERHORN-Fog, *Pure and Applied Geophysics*, DOI 10.1007/s00024-016-1352-6.

Wile, S.M., Hacker, J.P., and Chilcoat, K.H., 2015: The potential utility of high-resolution ensemble sensitivity analysis for observation placement during weak flow in complex terrain. *Weather and Forecasting*, *30*(6), 1521-1536.

Wang, Y., Creegan, E., Felton M., Huynh, G., Hocut, C., Fernando, H.J.S., Hoch, S., Whiteman, C.D., 2016: Triple Doppler wind lidar observations during the MATERHORN field project, *Journal of Applied Remote Sensing*, 10(2), 026015, 2016. doi: 10.1117/1.JRS.10.026015.

2017 (8)

Babic, N., Z. Vecenaj, S.F.J. De Wekker, 2017: Spectral gap characteristics in a daytime valley boundary layer. *Quarterly Journal of the Royal Meteorological Society*. DOI:10.1002/qj.3103

Jeglum, M. E., Hoch, S. W., Jensen, D. D., Dimitrova, R., and Silver, Z., 2017: Large Temperature Fluctuations due to Cold-Air Pool Displacement along the Lee Slope of a Desert Mountain. *Journal of Applied Meteorology and Climatology*, *56*(4), 1083-1098.

Lorente-Plazas, R. and J. P. Hacker, 2017: Observation and Model Bias Estimation in the Presence of Either or Both Sources of Error. *Monthly Weather Review*, https://doi.org/10.1175/MWR-D-16-0273.1.

Jensen, D. D., Nadeau, D. F., Hoch, S. W., and Pardyjak, E.R., 2017: The evolution and sensitivity of katabatic flow dynamics to external influences through the evening transition. *Quarterly Journal of the Royal Meteorological Society*, *143*(702), 423-438.

Kit, E., Hocut, C.M., Liberzon, D., and Fernando, H.J.S., 2017: Fine-scale turbulent bursts in stable atmospheric boundary layer in complex terrain, *Journal of Fluid Mechanics, Resubmitted with minor revisions.*

Massey, J.D., W.J. Steenburgh, S.W. Hoch, and D.D. Jensen, 2017: Simulated and observed surface energy balance contrasts and resulting playa breezes during the MATERHORN field

campaigns. *Journal of Applied Meteorology and Climatology*, doi.org/10.1175/JAMC-D-16-0161, 56, 915-935.

Morrison, T.J., Calaf, M., Fernando, H.J.S., Price, T.J., and Pardyjak, E.R., 2017: A methodology for computing spatially and temporally varying surface sensible heat flux from thermal imagery, *Quarterly Journal of the Royal Meteorological Society. In Press*, DOI: 10.1002/qj.3112.

Pu, Z., 2017: Surface data assimilation and near-surface weather prediction over complex terrain. Book Chapter, "*Data Assimilation for Atmospheric, Oceanic and Hydrologic Applications* (Vol. III)", Ed. By S.K. Park and L. Xu, Speinger. p219-240. DOI 10.1007/978-3-319-43415-5_10.[Book Chapter].

Papers Submitted or in Revision (Total: 13)

Arthur, R.S., Lundquist, K.A., Mirocha, J.D., Hoch, S.W., and F.K. Chow. 2017: High-resolution simulations of downslope flow over complex terrain using WRF-IBM, *Journal of Environmental Fluid Dynamics*, under revision.

Bao, J., Chow, F.K., and K.A. Lundquist, 2017: An immersed boundary method for complex terrain simulation in WRF, *Monthly Weather Reviewer*, submitted.

Chachere, C. and Z. Pu, 2017: Numerical simulations of an inversion fog event in the salt lake valley during the MATERHORN-Fog Field Campaign. *Pure and Applied Geophysics*, Submitted.

Conry, P., Kit, E., and Fernando, H.J.S., 2017: Measurements of mixing parameters in atmospheric stably stratified parallel shear flow, *Journal of Environmental Fluid Mechanics, submitted*

Duine, G.J., and S.F.J. De Wekker, 2017: The effects of horizontal grid spacing on simulated PBL depths in an area of complex terrain in Utah. Submitted to *Environmental Fluid Mechanics*.

Gunawardena, N., E.R. Pardyjak, R. Stoll, and A. Khadka, 2017: Development and evaluation of an open-source low-cost distributed sensor network for environmental monitoring applications, *Measurement Science and Technology*, Submitted.

Leo, L., Hocut, C., and Fernando, H.J.S., 2017:Upslope flows in complex terrain: Scaling and Observations, Ready to be submitted to *Journal of Environmental Fluid Mechanics*.

Nadeau, D.F., H.J. Oldroyd, E.R. Pardyjak, N. Sommer, S. W. Hoch, M.B. Parlange, 2017: Field observations of the morning transition over a steep slope in a narrow alpine valley, submitted, *Journal of Environmental Fluid Dynamics*.

Strycker, B., and T. Pratt, 2017: Retrieval of Soil Moisture Through a time-domain channel sounding technique", *Journal of Atmospheric and Oceanic Technology*. Submitted for Publication.

Zhang, H. and Z. Pu, 2014: Evaluation of an ensemble Kalman filter for analyses and forecasts in regions of complex terrain with observations during the MATERHORN field program. *Monthly Weather Review*, Submitted.

Zhang, F. and Z. Pu, 2017: Sensitivity of numerical simulations of near-surface atmospheric conditions during an ice fog event over heber valley to snow depth and surface albedo. Submitted to *Journal of Applied Meteorology and Climatology*.

Zhong, Q., Fernando, H.J.S., and Hussain, 2017: Quantification of mixing by colliding gravity currents, *Journal of Fluid Mechanics*, Submitted for publications.

Zhong, Q., Hussain, F., and Fernando, H.J.S., 2017: Application of Phase Averaging to Investigate Spasmodic Mixing in Environmental Flows, *Journal of Environmental Fluid Mechanics, in revision*

Invited Presentations: (Total: 31)

2012 (3)

Fernando, H.J.S. "Air Quality at Different Spatial Scales: Panel Discussion," Invited Speaker, 5th Annual CENSAM (Center for Environmental Sensing and Modeling) Workshop, MIT-Singapore Alliance, Jan 12-13, 2012.

Fernando, H.J.S., "Mixing in Stratified Shear Layers, including the Effects of Topography," Invited Speaker, Workshop on Physical Processes in the Bay of Bengal and Monsoon ISO. 5-7 March, Indian Institute of Sciences, Bangalore, 2012.

Fernando, H.J.S., Pardyjak, E., Zajic, D., De Wekker, S.J.F., and Pace, J., The Mountain Terrain Atmospheric Modeling and Observations (MATERHORN) Program: The First Field Experiment (MATERHORN-X1), Invited Paper, *American Geophysical Union*, Fall Meeting, Abstract # A12D-01, 2012.

2013 (2)

Chow, F.K. 2013. The immersed boundary method: enabling atmospheric simulations over highly complex terrain. UC Davis Conference on traversing new terrain in meteorological modeling, air quality and dispersion. Davis, California, September 10-12, 2013.

Fernando, H.J.S., Bhat, G.N. and Sharma, A., The Battle of Fluids: Air, Water and Climate, Keynote Speaker, 35th IAHR World Congress, Chengdu, China, September 8-13, 2013.

2014 (6)

Fernando, H.J.S., From Laboratory to Climate: Understanding of Multi-scale Processes through Observations, Invited Speaker, Mémorial Gabriel Chabert d'Hières Prospective sur la nouvelle plate-forme Coriolis, Université Joseph Fourier, Grenoble, France, 2014.

Fernando, H.J.S., Urbanization and Climate Change in Urban Metropolises, *Hong Kong Jockey Club Advanced Institute Lecture*, 12th December, 2014.

Higgins, C., Future directions in hydrologic measurement, Symposia honoring the Career of Dr. Richard Cuenca; Oregon State University, Corvallis OR; 11 April 2014.

Pardyjak, E.R, "The MATERHORN Experiments - Toward Improved Numerical Weather Prediction Complex Terrain Environments," Dugway Proving Ground, 11 September 2014.

Pardyjak, E.R., "Studying Multi-scale/Multi-physics Processes in Complex Terrain Environments for Improved Numerical Weather Prediction," Princeton University, 16 March 2014.

Pu, Z. and H. Zhang 2014, Evaluation of High-resolution Surface Analyses and Forecasts with Ensemble Kalman Filter Data Assimilation in Regions of Complex Terrain, Invited talk, Asia Oceanic Geosciences Society (AOGS) 11th Annual Meeting. July 28- August 1, 2014, Sapporo, Japan.

2015 (9)

Fernando, H.J.S., Turbulence and Fluxes in the Atmospheric Boundary Layer: Implications from Urban Street Canyon to Climate Scales, *Enrico Marchi Award Lecture*, Italian Hydraulics Association, June 12, 2015.

Fernando, H.J.S., Meteorology and Air Quality in Urban Areas in Complex Terrain: Effects of Climate Change and Rapid Expansion, 23rd (Korean Academy for Science and Technology International Symposium on *"Fine Particles: Causes, Impact and Mitigation"*, Diamond Hall, Plaza Hotel, Seoul, Korea, 17 September 2015.

Fernando, H.J.S., Urbanization and Climate Change in Urban Metropolises, Distinguished Lecture, *Hong Kong Jockey Club Advanced Institute Lecture*, Hong Kong University of Science and Technology, 12th December, 2014

Pardyjak, E.R., Overview of the University of Utah Environmental Fluid Dynamics Lab, *ARL Atmospheric Science Center Workshop* 2015, 9-10 Jun 2015, White Sands Missile Range.

Whiteman, C. D., 2015: Diurnal Mountain Winds. Innsbruck Summer School of Alpine Research on Surface-Atmosphere Exchange over Mountainous Terrain. 23-29 August 2015, Innsbruck, Austria. Invited talk.

Whiteman, C. D., 2015: Dynamically Driven Flows. Innsbruck Summer School of Alpine Research on Surface-Atmosphere Exchange over Mountainous Terrain. 23-29 August 2015, Innsbruck, Austria. Invited talk.

Whiteman, C. D., and R. Garibotti, 2015: Frozen on Peaks - The Geography, Meteorology and Physics of Rime Mushrooms. Utah State University Physics Colloquium, 29 September 2015. Invited talk.

Whiteman, C. D., and R. Garibotti, 2015: Southern Patagonia Ice Mushrooms. Innsbruck Summer School of Alpine Research on Surface-Atmosphere Exchange over Mountainous Terrain. 23-29 August 2015, Innsbruck, Austria. Invited talk.

Whiteman, C. D., and R. Garibotti, 2015: Southern Patagonia Ice Mushrooms. University of Utah OSHER Institute Lunch and Learn. 8 April 2015, Salt Lake City, UT. Invited talk.

2016 (8)

Chow, F.K., High-resolution simulations of flow over complex terrain: progress and challenges, *International Conference on Alpine Meteorology,* Innsbruck, Austria, September 2, 2015. [keynote speaker]

Chow, F.K. 2015. Challenges for high-resolution simulations of atmospheric flow over complex terrain. Abstract NG13B-05 presented at *2015 AGU Fall Meeting,* San Francisco, California, 14-18 December. [Invited talk]

De Wekker, S.F.J.,.2015: Convective boundary layers over mountains. Innsbruck Summer School of Alpine Research on Surface-Atmosphere Exchange over Mountainous Terrain. 23-29 August 2015, Innsbruck, Austria [Invited talk]

De Wekker, S.F.J., 2015: Numerical modeling of the atmosphere in complex terrain. Innsbruck Summer School of Alpine Research on Surface-Atmosphere Exchange over Mountainous Terrain. 23-29 August 2015, Innsbruck, Austria [Invited talk]

Fernando, H.J.S., Kit, E., Sukorianski, S. and Hocut, C.M., Turbulent Bursts in the Stable Atmospheric Boundary Layer, IMA Conference on Turbulence, Waves and Mixing, Wednesday 6 – Friday 8 July 2016, King's College Cambridge, UK, 2016. [Invited talk]

Fernando, H.J.S., Hacker, J., Katopodes Chow, F., Pardyjak, E., and de Wekker, S.F.J., The Mountain Terrain Atmospheric Modeling and Observations (MATERHORN) Program (2011-2016), 20th Annual George Mason University (GMU) Conference on Atmospheric Transport and Dispersion Modeling, GMU Fairfax, Virginia June 14-16, 2016. [Invited talk]

Pardyjak, E.R., "Transitional and stable boundary-layer processes in complex terrain during the MATERHORN field campaign," Laboratoire d'Aérologie, L'Observatoire Midi-Pyrénées (OMP), l'Université Toulouse III - Paul Sabatier (UPS), Toulouse, France, 1 December 2016 [Invited Talk].

Pu, Z., Surface data assimilation and near surface weather forecasting over complex terrain. AOGS 13th Annual Meeting, 31 July to 5 Aug, 2016, Beijing, China. [Invited talk]

2017 (3)

Fernando, H.J.S., Climate Change in Cities, *Invited Speaker*, Workshop on Urban Microclimate: From Research to Application, Singapore, 26th April, 2017 [Invited keynote speaker].

Pardyjak, E.R., "Investigating spatial heterogeneity of thermal circulations and turbulence in complex terrain," ACINN Seminar, University of Innsbruck, Austria, 17 May 2017.

Pu, Z., *Invited Speaker*, Numerical prediction and data assimilation over complex terrain: Lessons learned from MATERHORN. 1st Workshop for Mountain Terrain Atmsopheric Observations and Modeling (MOUNTAOM WS-1). 21-23 June 2017. Beijing, China [Invited Talk]

Conference Papers (Total: 13)

2011 (2)

Fernando, H.J.S., Leo, S.L., DiSabatino, S., Dallman, A. "Evening Transition in Inland and Coastal Mountainous Terrain," AMS 91st Annual Meeting, 23-27 January, Seattle, WA, paper 4.5, January 2011.

Monti, P., Fernando, H.J.S. and Princevac, M., "Waves and Turbulence Contributions to Stratified Turbulence in Katabatic Flows," Proceedings, 7th International Symposium of Stratified Flows, (Ed. A. Cenedese), 22-26 August, 2011.

2012 (5)

De Wekker, S.F.J., 2012: Convective Boundary Layer Heights in Mountainous Terrain. New Insights From Observations in the Appalachian Mountains. 17th AMS Conference on Air Pollution Meteorology with the A&WMA, New Orleans, LA, 22-26 January 2012.

DiSabatino, S., Leo, L., Liberzon, D., Retallack, C., Coppersmith, R.S., Sentic, S., Huq, P., Hocut, C., Fernando, S. and Fernando, H.J.S., Evening Transition of Atmospheric Boundary Layer (ABL) in Heterogeneous Flat Terrain," American Meteorological Society 92nd Annual Meeting, New Orleans, 2012

Fernando, H.J.S. The Mountain Terrain Atmospheric Modeling and Observations (MATERHORN) Program: An Overview, Extended Abstract, American Meteorological Society 92nd Annual Meeting, New Orleans, Paper 11.12, 2012.

Leo, L., DiSabatino, S, and Fernando, H.J.S., Flow in Complex Terrain with Coastal and Urban Influence, American Meteorological Society 92nd Annual Meeting, New Orleans, Paper 11.1, 2012.

Simon, J.S., K.A. Lundquist, and F.K. Chow. 2012. Application of the immersed boundary method to simulations of flow over steep, mountainous terrain. Paper 45. 15th Conference on Mountain Meteorology, American Meteorological Society, 9 pages.

2014 (1)

Wiersema, D.J., Lundquist, K.A., and F.K. Chow. 2014. Enabling multi-scale simulations in WRF through vertical grid nesting. Paper 9B.5. *21st Symposium on Boundary Layers and Turbulence,* American Meteorological Society, 9 pages.

2016 (3)

Arthur, R. S., Lundquist, K. A., Mirocha, J. D., Hoch, S. W., & Chow, F. K. 7.6 High-resolution simulations of downslope flows over complex terrain using WRF-IBM. 17th Conference on Mountain Meteorology, American Meteorological Society, 18 pages.

Bao, J., Lundquist, K.A., and F.K. Chow. 2016. Comparison of three different implementations of the immersed boundary method in WRF (WRF-IBM). Paper 4B.5. *21st Symposium on Boundary Layers and Turbulence*, American Meteorological Society, 11 pages.

Fernando, H.J.S., Kit, E., Sukorianski, S., and Hocut, C., Turbulent Bursts in the Stable Atmospheric Boundary Layer, In: Turbulence, Waves and Mixing: In Honor of Lord Julian Hunt's 75th Birthday, Institute of Mathematics and its Application (Eds: S.G. Sajjidi and H.J.S. Fernando; ISBN 978-0-905091-35-8).

2017 (2)

Pu, Z., 2017: Enhancing Surface Data Assimilation Through Removing Systematic Forecast Biases. *21st Conference on Integrated Observing and Assimilation Systems for the Atmosphere, Oceans, and Land Surface.* 97th AMS Annual Meeting, January 22-26, 2017, Seattle, CA.

Zhang, F. and Z. Pu, 2017: Sensitivity of Numerical Simulations of an Ice Fog Event to PBL and Surface Layer Parameterization Schemes with WRF model. *28th Conference on Weather Analysis and Forecasting / 24th Conference on Numerical Weather Prediction.* 97th AMS Annual Meeting, January 22-26, 2017, Seattle, CA.

Conference Presentations (Total: 179)

2011 (10)

De Wekker, S.F.J., J. Doyle, Q. Jiang, K. Godwin, E. Erfani, G. D. Emmitt, 2011: Investigation of multi-scale flow interaction in the Salinas Valley using a combination of airborne Doppler lidar data and a mesoscale numerical model. AGU Fall meeting, San Francisco, CA, 5–9 December 2011.

Liberzon, D, Hocut, C. and Fernando, H.J.S., Thermally Driven Upslope Flow in Mountainous Terrain, *Bull. Am. Phys. Soc.*, **56(18)**, 216, 2011.

Lozovatsky, I. and Fernando, H.J.S., Mixing Efficiency in Natural Flows, 3rd International Conference 'Turbulent Mixing and Beyond', Trieste, Italy, 21 July - 28 August, 2011.

Pardyjak, E.R., D. Alexander, M. Lothon, F. Lohou, S. Derrien; J. Reuder, D. Legain, O. Traulle, H. Pietersen, O. Decoster, G. Canut, C. Darbieu, A. Garai, E. Pique, 2011: First results from the surface heterogeneity focus area of the Boundary Layer Late Afternoon and Sunset Turbulence (BLLAST) Experiment, Abstract A41A-0034, presented at 2011 Fall Meeting, AGU, San Francisco, Calif., 5-9 Dec.

Pu, Z. and H. Zhang and X. Zhang, 2011: The impact of surface data assimilation on the: On the assimilation of surface observations over complex terrain: EnKF vs. 3DVAR. *AGU Fall Meeting*. December 5-9, 2011. San Francisco, CA.

Retallack, C., H. Fernando, E. Pardyjak, S.F.J. De Wekker, J.C Pace, 2011: The MATERHORN Experiment. AGU Fall meeting, San Francisco, 5–9 December 2011.

Whiteman, C. D. and S. W. Hoch, M. Jeglum and L. Campbell: MATERHORN-X Field Studies. MATERHORN Kick-off Meeting, Salt Lake City, UT., 8 Sept. 2011.

Zajic, D., J. C. Pace, C. D. Whiteman, and S. Hoch, 2011: The Granite Mountain Atmospheric Sciences Testbed (GMAST): A Facility for Long Term Complex Terrain Airflow Studies. AGU Fall Meeting, 5-9 December 2011, San Francisco, CA.

Zhang, H., C. W. Pace and Z. Pu, 2011: Evaluation of the Diurnal Variation of near-Surface Temperature and Winds from WRF Numerical Simulations over Complex Terrain, *AGU Fall Meeting*. December 5-9, 2011. San Francisco, CA.

Zhang and X. Zhang, 2011: The impact of surface data assimilation on the Pu, Z. and H. Zhang: On the assimilation of surface observations over complex terrain: EnKF vs. 3DVAR. *AGU Fall Meeting*. December 5-9, 2011. San Francisco, CA.

2012 (21)

Dallman, A., DiSabatino, S., Leo, L.S. and Fernando, H.J.S., "Flow Characteristics in an Urban Area Located in Complex Terrain," American Meteorological Society 92nd Annual Meeting, New Orleans, Paper 11.4, 2012.

Farley-Chrust, M., C. D. Whiteman and S. W. Hoch: Observations of Wind Jets at the Exit of Weber Canyon, Utah. 15th Conference on Mountain Meteorology, Steamboat Springs, CO, 20-24 August 2012.

Fernando, H.J.S. and Lozovatsky, I., Mixing Efficiency in Natural Flows, *Ocean Sciences Meeting*, TOS/AGU/ASLO Proc., 110, 2012.

Hocut, C., Liberzon, D. and Fernando, H.J.S., "Thermally Driven Upslope Flow Separation in Steep Mountainous Terrain," 15th AMS Conference on Mountain Meteorology, 20-24, August, 2012.

Hocut, C., Liberzon, D. and Fernando, H.J.S., "Thermally Driven Upslope Flow in Mountain Terrain," American Meteorological Society 92nd Annual Meeting, New Orleans, Paper 11.3, 2012.

Jeglum M. E, S. W. Hoch, C. D. Whiteman, and J. D. Massey: Land-Surface Contrasts and Thermally Driven Flows at Dugway Proving Ground, Utah. 15th Conference on Mountain Meteorology, Steamboat Springs, CO, 20-24 August 2012

Massey, J. D., W. J. Steenburgh, J. C. Kneivel, M. E. Jeglum, and S. W. Hoch, 2012: Observations and modeling of thermally driven flows over the Great Salt Lake Desert. 15th Conference on Mountain Meteorology, American Meteorological Society, 20-24 Aug 2012.

Oldroyd, H.J., E. Pardyjak, M. Calaf, D.F. Nadeau, M. Hultmark, and M.B. Parlange, Steep slope flow observations during the morning transition in a narrow alpine valley. Abstract A13C-0243, presented at 2012 Fall Meeting, AGU, San Francisco, Calif., 3-7 Dec.

Pardyjak, E.R., D. Nadeau, C. Higgins, H. Huwald, and M. B. Parlange, 2012. Developing an improved understanding of steep slope evening transition processes. 92nd American Meteorological Society Annual Meeting, January 22-26, 2012, New Orleans, 11.6.

Pu, Z. and H. Zhang, 2012: Evaluation of the Diurnal Variation of near-Surface Temperature and Winds From WRF Numerical Simulations Over Complex Terrain and the Impact on Assimilation of Surface Observations, *17th Conference on Air Pollution Meteorology with the A&WMA*, January 22-27, 2012, New Orleans, LA

Pu, Z. and H. Zhang, 2012: Examination of Flow-Dependent Errors in Near-Surface Temperature and Wind from WRF Numerical Simulations over Complex Terrain. 3rd WRF Users Workshop, June 26-29. 2012.

Pu, Z., H. Zhang and X. Zhang, 2012: Data assimilation over complex terrain. Materhorn Annual Review Meeting, Salt Lake City, UT, August 17, 2012.

Retallack, C., Fernando, H.J.S and Hunt, J.C.R., "Turbulent stratified flows over orography with large scale forcing-concepts and idealized models," 15th AMS Conference on Mountain Meteorology, 20-24, August, 2012.

Simon, J.S., Lundquist, K.A., and F.K. Chow. 2012. Application of the immersed boundary method to simulations of flow over steep, mountainous terrain. *15th Conference on Mountain Meteorology,* Steamboat Springs, Colorado, August 20-24, 2012.

Simon, J., Lundquist, K.A. and F.K. Chow. 2012. Addressing the "terra incognita" – appropriate representation of terrain from mesoscale to microscale. Abstract A13C-0242 presented at 2012 AGU Fall Meeting, San Francisco, California, 3-7 December. [Poster]

Večenaj, Ž. and S.F.J. De Wekker,2012: Nonstationarity in the surface layer over complex terrain during T-REX. 15th AMS Conference on Mountain Meteorology, Steamboat Springs, CO, 20-24 August 2012.

Večenaj, Ž. and S.F.J. De Wekker, 2012: Exploring Monin-Obukhov similarity in the surface layer over complex terrain during T-REX. 15th AMS Conference on Mountain Meteorology, Steamboat Springs, CO, 20-24 August 2012.

Večenaj, Ž. and S.F.J. De Wekker, 2012: Averaging Time Scale for Daytime Turbulent Flux Measurements in a Wide and Steep Valley. 17th AMS Conference on Air Pollution Meteorology with the A&WMA, New Orleans, LA, 22-26 January 2012.

Zajic, D., J. C. Pace, C. D. Whiteman, and S. W. Hoch, 2012: An Overview of the Granite Mountain Atmospheric Sciences Testbed (GMAST). 17th Conference on Air Pollution Meteorology with the A&WMA, January 2012, New Orleans, LA.

Zhang, H. and Z. Pu, 2012: Examination of flow-dependent errors in near-surface temperature and winds from WRF numerical simulations over complex terrain. AMS 15th Conference on Mountain Meteorology, Steamboat, CO, August 20-24, 2012

Zhou, B. and F.K. Chow. 2012. Nighttime Cold-Air Intrusions and Transient Warming in a Steep Valley: A Nested Large-eddy Simulation Study. Paper 3.2. 15th Conference on Mountain Meteorology, American Meteorological Society.

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Arthur, R. S., K. A. Lundquist, J. D. Mirocha, S. W. Hoch, and F. K. Chow, 2016: High-resolution Simulations of Downslope Flows Over Complex Terrain Using WRF-IBM. 17th Conference on Mountain Meteorology, 27 June – 1 July 2016 Burlington, VT.

Babic, N., and S.F.J. De Wekker, 2016: Coherent structures over complex terrain and their contribution to vertical fluxes of momentum and heat. 17th AMS Conference on Mountain Meteorology, 27 June – 1 July 2016, Burlington, VT.

Chachere, C. and Z. Pu, 2016: Sensitivity of numerical prediction of fog events to WRF model physical parameterization schemes: A study with MATERHORN fog-X observations. *19th Joint Conference on the Applications of Air Pollution Meteorology with the A&WMA*. 96th AMS annual Meeting. January 09-14, 2016. New Orleans, LA

Chow, F.K., A.D. Anderson-Connolly, R.S. Arthur, and K.A. Lundquist. 2016: Simulation of stable flows over Granite Mountain. Presentation 4B.4. *21st Symposium on Boundary Layers and Turbulence*. American Meteorological Society.

Chow, F.K., J. Bao, and K.A. Lundquist. 2016: Progress in generalizing the immersed boundary method in WRF for flow over complex terrain. Presentation 2.1. *17th Conference on Mountain Meteorology*. American Meteorological Society.

Creegan, Edward D., C. M. Hocut, Y. Wang, Z. Silver, S. Hoch, L. S. Leo, S. Di Sabatino, H. J. S. Fernando, and E. Pardyjak, 2016: Synoptic Flow Interactions with an Isolated Mountain in Complex Terrain. 96th American Meteorological Society Annual Meeting, New Orleans, LA, 10–14 January 2016.

De Wekker, S.F.J., C.D. Whiteman, S.W. Hoch, and M. E. Jeglum, 2016: Thermally Driven Winds Across Gaps in a Linear Mountain Chain. 17th AMS Conference on Mountain Meteorology, 27 June – 1 July 2016, Burlington, VT.

De Wekker, S.F.J., and S. Serafin, 2016: Investigating convective boundary layer heights over mountain ridges. 19th Joint AMS Conference on the Applications of Air Pollution Meteorology with the A&WMA. 10-14 January 2016, New Orleans, LA.

De Wekker, S.F.J., N. Rose and R. Palomaki, 2016: Atmospheric Boundary Layer Investigations Using an Instrumented Multi-Rotor Copter. 18th AMS Symposium on Meteorological Observation and Instrumentation. 10-14 January 2016, New Orleans, LA.

Dimitrova, R., S. Silver, T. Zsedrovits, and H.J.S. Fernando, 2016: Numerical simulations for stably stratified flow in complex terrain for MATERHORN field program, III Bulgarian Conference In Physics, September 29-October 2, Sophia, Bulgaria.

Di Sabatino, Silvana, L.S. Leo, H.J. S. Fernando, E.R. Pardyjak, M. Lehner, C.D. Whiteman, and S. Hoch, 2016: Observations of evening and morning transition in valleys and slopes, 2016: 96th American Meteorological Society Annual Meeting, New Orleans, LA, 10–14 January 2016.

Duine,G.-J., and S.F.J. De Wekker, 2016: Considerations on the Importance of Planetary Boundary Layer Depths over Complex Terrain for Carbon Cycle Studies. 17th AMS Conference on Mountain Meteorology, 27 June – 1 July 2016, Burlington, VT.

Duine,G.-J., and S.F.J. De Wekker, 2016: Influence of Subgrid Terrain Variability on Simulated Planetary Boundary Layer Depths in Large-scale. Transport Models. 44th Global Monitoring Annual Conference, May 17-18, 2015, Boulder, CO.

Fernando, H.J.S., P. Conry, E. Kit, C. Hocut, D. and Liberzon, 2016: Turbulence in the Stable Atmospheric Boundary Layer, *Bull. Am. Phys. Soc.*, 61(20), xxx, 2016.

Gultepe, I., A.J. Hemsfield, H.J.S. Fernando, S. Hoch, and R. Ware, 2016: UAV applications for thermodynamical profiling: Emphasis on ice fog research, EGU General Assembly Meeting, Vienna, Austria, 77-22 April, 2016.

Gultepe, I., E.R. Pardyjak, S.W. Hoch, S.W. Silver, W. Burrows, H.J.S. Fernando, E. Creegan, L.S. Leo, A.J. Heymsfield, M. Pavolonis, R. Ware, T. Kuhn, R. Rabin, B. Zhou, Z. and Pu, 2016: Ice Fog as high impact weather: Measurement and Prediction issues, IFFCD conference, Poland, July 2016.

Gultepe, Ismail, L.S. Leo, E.R. Pardyjak, S. Hoch, E. Creegan, Z. Silver, S.D. Wekker, and H.J. S. Fernando, 2016: Ice Fog Microphysical Properties at High Elevations: MATERHORN Observations and Parameterizations. 96th American Meteorological Society Annual Meeting, New Orleans, LA, 10–14 January 2016

Gunawardena, N. and E.R. Pardyjak, 2016: The Use of Artificial Neural Networks Within Boundary Layer Meteorology, American Meteorol. Soc., 20-24 June 2016, Salt Lake City, 95.

Hang, C., D. Nadeau, D. Jensen, S.W. Hoch, and E.R. Pardyjak, 2016: Evaporation from a Desert Playa Following Rainfall. 22nd Symposium on Boundary Layers and Turbulence, 20 – 24 June 2016, Salt Lake City, UT.

Hang, C., D. Nadeau, I. Gultepe, S. Hoch, H.J.S. Fernando, E. Creegan, L. Leo, Z. Silver, and E. Pardyjak, 2016: A Case Study of the Formation, Evolution and Dissipation of Ice Radiation Fog in a Mountain Valley. 22nd Symposium on Boundary Layers and Turbulence, 20 – 24 June 2016, Salt Lake City, UT

Hoch, S.W., and E.R. Pardyjak, 2016: Observations of Radiative Flux Divergence under Clear Sky and Fog Conditions. 22nd Symposium on Boundary Layers and Turbulence, 20 – 24 June 2016, Salt Lake City, UT.

Hoch, S.W. and E.R. Pardyjak, 2016: Observations of Radiative Flux Divergence under Clear Sky and Fog Conditions, American Meteorol. Soc., 20-24 June 2016, Salt Lake City, 29.

Hoch, S.W., E.T. Crosman, M. Baasandorj, J.C. Lin, R. Bares, R.S. Martin, J. Sohl, J.D. Horel, and C.D. Whiteman, 2016: Case Study of the 6-16 February 2016 Salt Lake Valley

Persistent Cold-Air Pool. 17th Conference on Mountain Meteorology, 27 June – 1 July 2016 Burlington, VT.

Hocut, C.M., E. Kit, D. Liberzon, and H.J.S. Fernando, 2016: Fine-Scale Turbulent Bursts in Stable Atmospheric Boundary Layer in Complex Terrain. 32nd Conf. on Agricultural and Forest Meteorology/22nd Symp. Boundary Layers and Turbulence/ Third Conf. on Atmospheric Biogeosciences, Salt Lake City, Utah, 20 – 24 June, 2016.

Jensen, D., D.F. Nadeau and E.R. Pardyjak, 2016: Assessing the effect of soil moisture on katabatic flow dynamics over a shallow slope during the MATERHORN field program, 96th American Meteorological Society Annual Meeting, 10-14 January 2016, New Orleans, 10.2.

Jensen, D.D., D. Nadeau and E.R. Pardyjak, 2016: The Sensitivity of Katabatic Flow Dynamics to External Influences through the Evening Transition, American Meteorol. Soc., 20-24 June 2016, Salt Lake City, 9A.6.

Lundquist, K.A., M.H. Daniels, J.D. Mirocha, D.J. Wiersema, and F.K. Chow, 2016: A new vertical grid nesting capability for multiscale simulations using the WRF model. Presentation 3B.4. *21st Symposium on Boundary Layers and Turbulence*, American Meteorological Society.

Marinović, I., N. Babic, Z. Vecenaj, I. Stiperski, and S.F.J. De Wekker, 2016: Surface Energy Balance Closure in the Owens Valley, CA. 17th AMS Conference on Mountain Meteorology, 27 June – 1 July 2016, Burlington, VT.

Nilsson, E., M. Lothon, F. Lohou, C. Darbieu, E.R. Pardyjak, O.K. Hartogensis, and L. Mahrt, 2016: Turbulence kinetic energy decay in the afternoon transition, 22nd Symp. Boundary Layers and Turbulence, American Meteorol. Soc., 20-24 June 2016, Salt Lake City, 3A.2.

Oldroyd, H.J., E.R. Pardyjak, C. Higgins, and M.B. Parlange, 2016: Counter-Gradient, Co-Gradient and 'Surface-Layer' Momentum Fluxes in Nocturnal Slope Flows over Steep Alpine Terrain, American Meteorol. Soc., 20-24 June 2016, Salt Lake City, 37.

Oldroyd, H.J., E.R. Pardyjak, C. Higgins, and M.B. Parlange, 2016: Nocturnal buoyant TKE production in steep-slope katabatic flows: Observations, theory and multi-scale transport dynamics, American Meteorol. Soc., 20-24 June 2016, Salt Lake City, 9A.7.

Pu, Z., and C. Chachere, 2016: Numerical prediction of fog events over mountainous terrain: Sensitivity to model physics, data assimilation and visibility algorithms. AMS 22nd Symposium on Boundary Layers and Turbulence. June 20-24, 2016, Salt Lake City, UT

Pu, Z. and L. Zhang, 2016: Assimilation of MATERHORN field program data for better understanding and prediction of mountainous atmospheric flows over complex terrain. *19th Joint Conference on the Applications of Air Pollution Meteorology with the A&WMA.* 96th AMS annual Meeting. January 09-14, 2016. New Orleans, LA

Serafin, S., and S.F.J. De Wekker, 2016: A modelling study of the factors governing the convective boundary layer height over isolated mountain ridges. 17th AMS Conference on Mountain Meteorology, 27 June – 1 July 2016, Burlington, VT.

Silver, Z., Dimitrova, R. , Zsedrovits, T. , Fernando, H. J. S. , Leo, L. S., Di Sabatino, S., Serafin, S., Wang, Y., Creegan, E. D., Felton, M., Hocut, C. M., 2016: WRF Simulations of Synoptic Flow Modification over Mountainous Terrain during MATERHORN Observation Periods, 96th American Meteorological Society Annual Meeting, New Orleans, LA, 10–14 January 2016.

Silver, Z., Dimitrova, R., Fernando, H. J. S., Zsedrovits, T., 2016: WRF Simulations for Stably Stratified Observation Periods of the MATERHORN Spring Field Campaign with

Application to the Dividing Streamline, 17th Conference on Mountain Meteorology, 27 June – 1 July 2016 Burlington, VT.

Whiteman, C.D., M. Lehner, S.W. Hoch, B. Adler, N. Kalthoff, and M.O.G. Hills, 2016: Lifting of Stable Layers Over a Circularly Symmetrical Terrain Obstacle. 17th Conference on Mountain Meteorology, 27 June – 1 July 2016 Burlington, VT.

Wiersema, D.J., K.A. Lundquist, and F.K. Chow, 2016: A framework for WRF to WRF-IBM grid nesting to enable multiscale simulations. Poster 38. *21st Symposium on Boundary Layers and Turbulence,* American Meteorological Society.

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Di Sabatino, S., Leo L.S., Pardyjak, E.R., and Fernando, H.J.S., Boundary-layer processes: key findings from MATERHORN-X field Campaigns, Geophysical Research Abstracts Vol. 19, EGU2017-15550, 2017, EGU General Assembly17-22 April 2017.

Gultepe, I., Heymsfield, M., Fernando, H.J.S., Hoch, S., Pardyjak, E.J., Boudala, F., and Ware, S., UAV Applications for Thermodynamic Profiling:Emphasis on Ice Fog Visibility, Geophysical Research Abstracts Vol. 19, EGU2017-10439, 2017, EGU General Assembly17-22 April 2017.

Hacker, J.P. and Raquel Lorente-Plazas: An Approach to Reduce Systematic Representativeness Errors of Surface Observations in Ensemble Data Assimilation. 21st Conference on Integrated Observing and Assimilation Systems for the Atmosphere, Oceans, and Land Surface. AMS Annual Meeting, 23 Jan. 2017, Seattle, WA.

Lorente-Plazas, R., J.P. Hacker, N. Collins, and J. A. Lee: *Estimation and correction of different flavors of surface observation biases in ensemble Kalman filter.* EGU2017-11596. 2017, EGU General Assembly 17-22 April 2017.

Babic, N., Z. Vecenaj, S.F.J. De Wekker, 2017: Characteristics of the spectral gap in a valley convective boundary layer. 34th International Conference on Alpine Meteorology (ICAM), 18-23 June 2017, Reykjavik, Iceland.

Duine, G-J., S.F.J. De Wekker, 2017: Influence of horizontal grid spacing in mountainous terrain on simulated planetary boundary layer depths in large-scale transport models. 34th International Conference on Alpine Meteorology (ICAM), 18-23 June 2017, Reykjavik, Iceland.

Babic, N., S.F.J. De Wekker, 2017: Convective plumes in a daytime valley atmosphere: Structure, scaling and flux contributions. 34th International Conference on Alpine Meteorology (ICAM), 18-23 June 2017, Reykjavik, Iceland.

Wolf, C.A, R.P. Hardis, S.D. Woodrum, R.S. Galan, H.S. Wichelt, M.C Metzger, N. Bezzo, G.C Lewin, and S.F.J. De Wekker, 2017: Wind Data Collection Techniques on a Multi-Rotor Platform. IEEE Systems and Information Engineering Design Symposium (SIEDS'17), 28 April 2017. Charlottesville, VA.

Marinović, I., N. Babic, Z. Vecenaj, I. Stiperski, and S.F.J. De Wekker, 2017: Surface energy balance closure in the Owens Valley, CA, Joint Congress of the 6th International Conf. on Meteorology and Climat. of the Mediterranean & Challenges in Meteorology 5, Zagreb, Croatia, 20-22 February 2017

Awards (Total: 11)

Ann Dallman – *Second place for the Best Student Oral Presentation*, 92nd Annual Meeting of the American Meteorological Society, 17th Conference on Air Pollution Meteorology, Jan 22-26, New Orleans, 2012.

Christopher Hocut, *Best Overall Presentation*, 92nd Annual Meeting of the American Meteorological Society, 17th Conference on Air Pollution Meteorology, Jan 22-26, New Orleans, 2012.

Jeff Massey, 3rd place, Best Student Poster, 15th Conference on Mountain Meteorology.

Jeff Massey, Best Student Oral Presentation, 18th Joint Conference on the Applications of Air Pollution Meteorology.

Mark Sghiatti – Second place for the Best Student Poster Presentation, 93rd Annual Meeting of the American Meteorological Society, 18th Joint Conference on the Applications of Air Pollution Meteorology with the A&WMA, Atlanta, GA, 3-7 February 2014.

C. David Whiteman, American Meteorological Society. Mountain Meteorology Award 2014.

Bowen Zhou - 3rd place - best oral presentation at 15th AMS Mountain Meteorology Conference, 2014.

H.J.S. Fernando, Enrico Marchi Award, Italian Hydraulics Association, 2015.

Fotina Katopodes Chow, Henry G. Houghton Award, American Meteorological Society, 2015.

Patrick Conry, Outstanding Student Paper Award, American Meteorological Society, 96th Annual Meeting, Atlanta, Jan 10-14, 2016.

Zachariah Silver, First Prize, 19th Conference on Air Pollution Meteorology, 96th Annual Meeting, Atlanta, Jan 10-14, 2016

Recognitions (Total: 6)

H.J.S. Fernando was elected as Fellow, American Association for the Advancement of Science (AAAS), 2012.

H.J.S. Fernando was Awarded *Doctor Honoris Causa*, Universitê Joseph Fourier (University of Grenoble), France, 2014.

H.J.S. Fernando, Awarded *Doctor of Laws, Honoris Causa*, by University of Dundee, Scotland, 2016.

H.J.S. Fernando, Nels Nelson Distinguished Lecture, University of Minnesota, 2016.

H.J.S. Fernando, Borland Hydraulics Lecture Award, Hydrology Days Conference, 2017.

H.J.S. Fernando, 49th Annual Alan Berman Research Publication Award, Naval Research Laboratory, 2017.

Number of Post Docs (Total: 18)

Dan Liberzon	2010 June -2012 July	University of Notre Dame
Laura Leo	2011 August – continuing as RAP	University of Notre Dame
Charles Retallack	2011 June -2012 October	University of Notre Dame
Raquel Lorente-Plazas	2014 August – 2016 August	University of Notre Dame
Chris Hocut	2014 January – June 2015.	ARL Post doc/Notre Dame
Dr. Qiang Zhang	September 2014 - continuing	University of Notre Dame
Tamas Zsedrovits	May 2013 to September 2013	University of Notre Dame
Raghavendra Krishnamurty	August 2016 - continuing	University of Notre Dame

Raquel Lorente	August 2014-2017	Notre Dame/NCAR
Zeljko Vecenai	March-September 2012	University of Virginia
Sandip Pal	February 2013 – August 2015	University of Virginia
Jared Lee	2013-2014	Naval Postgraduate School
Walter Kolczynski	2013-2013	Naval Postgraduate School
Vigneshwaran Kulandaivelu	2012-2014	University of Utah
Manuela Lehner	Part time, FY13-14	University of Utah
Michael van den Bossche	January 2014 - present	University of Virginia
Gert-Jan Duine	March 2016 – present	University of Virginia
Robert Arthur	Oct 2015-Feb 2017	U. California, Berkeley

Number of Graduate Students (Total: 21 PhD Students, 9 MS Students)

Jordan Bryant	MS	University of Notre Dame	Esteem Fellow
Catherine Chachere	MS	University of Utah	MS 2016 completed
Zi Lin	MS	University of Notre Dame	MS 2014 completed
Kelly McEnerney	MS	University of Notre Dame	MS 2014 Completed
Ross Palomaki	MS	University of Virginia	partial support
Mark Sghiatti	MS	University of Virginia	MS 2016 completed
Yinjie Sun	MS	University of Notre Dame	MS 2013 completed
Michael Thompson	MS	University of Notre Dame	MS 2014 completed
Xuebo Zhang	MS	University of Utah	partial support
Nevio Babic	PhD	University of Virginia	partial support
Jingyi Bao	PhD	University of California, Berkeley	
Estel Blay Carreras	PhD	University of Utah	visiting student
Carlos Roman Cascon	PhD	University of Utah	visiting student
Patrick Conry	PhD	University of Notre Dame	NDSEG, PhD 2017
Ehsan Erfani	PhD	University of Virginia	January-April 2012
Nipun Gunawardena	PhD	University of Utah	partial support
Chaoxun Hang	PhD	University of Utah	PhD 2017 completed
Christopher Hocut	PhD	University of Notre Dame	PhD 2014 completed
Maj. Paul Homan	PhD	Naval Postgraduate School	
Matthew Jeglum	PhD	University of Utah	PhD 2016 completed
Derek Jensen	PhD	University of Utah	PhD 2016 completed
Jeff Massey	PhD	University of Utah	PhD 2015 completed
Alexei Perelet	PhD	University of Utah	partial support
Zachariah Silver	PhD	University of Notre Dame	PhD 2016 completed
Jason Simon	PhD	University of California, Berkeley	(until July 2013)
Alex Anderson-Connolly	PhD	University of California, Berkeley	
Capt. Sean Wile	PhD	Naval Postgraduate School	
Hao Wang	PhD	University of Notre Dame	
Hailing Zhang	PhD	University of Utah	partial support

Number of Undergraduate Students (Total: 30)

Greg Brownell	University of Notre Dame	2012
Jordan Bryant	University of Notre Dame	current
Patrick Conry	University of Notre Dame	06/11 to 01/13
Ian deBoisblanc	University of Virginia	summer 2013
Nikita Dodbele	University of Virginia	summer 2013
Sahan Fernando	University of Notre Dame	summer 2012
Nipun Gunawardena	University of Utah	2012/2013
Andrew Harper	University of Notre Dame	current
James Herrick	University of Notre Dame	2014
Mike Higginson	University of Notre Dame	2012
Derek Hodges	University of Utah	summer 2014
Christan Holbert	University of Utah	2012
Amy Kryston	University of Notre Dame (Gonzaga University), summer 2015	
Lee Kussmann	University of Virginia	summer 2013
Gage Morrow	University of Virginia	summer 2014
Rahul Mukherji	University of Virginia	summer 2013
Max Newman	University of Virginia	summer 2013
Kevin Peters	University of Notre Dame	2012
Jasris Rapia	University of Notre Dame	2013
Nathan Rose	University of Virginia	January-August 2015
Thomas Sherman	University of Virginia	January-April 2015
Rich Strebinger	University of Notre Dame	2012
Kristin Stryker	University of Notre Dame	2012
Capt. Samuel White	University of Notre Dame	current
Santiago Espinoza Wilde	University of Notre Dame	2014 summer and Fall, 2015
Stef Broadel	University of Notre Dame	2016 summer
Kelly Valenzi	University of Notre Dame	2016 summer (Slatt Fellow)
Luis Fernandez	University of Notre Dame	2017 summer (Slatt Fellow)
John Salvadore	University of Notre Dame	2017 summer (Slatt Fellow)
Patrick Scholl	University of California, Berkeley	2016, 2017 summer